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Preliminary modelling of sediment transport on the upper foreslope of the Fraser River delta

Philip R. Hill and Susan H. Davidson

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Abstract: A preliminary modelling study of sediment transport on the foreslope of the Fraser River delta was carried out using the SEDTRANS96 model in preparation for a field measurement program. The model was run for water depths of between 2 and 40 m at a hypothetical site off Roberts Bank using a range of typical wave and current conditions. The results indicate that strong combined wave and current conditions would exist in water depths of less than 20 m under moderate storm conditions. Wave-dominated ripples and plane bed were predicted to be the predominant bedforms inshore of 15 m depth under moderate steady current velocities, but plane bed predominated when the steady current was higher. Predicted sediment transport directions are highly sensitive to wave direction. These results have been used to site a sediment transport monitoring instrument package in February 2002.

Résumé : En vue de réaliser un programme de mesure sur le terrain, on a mené, au moyen du modèle SEDTRANS96, une étude de modélisation provisoire du transport sédimentaire sur l'avant-talus du delta du fleuve Fraser. Pour le modèle, on a utilisé un site hypothétique au large du banc Roberts dans des conditions de vagues et de courants typiques, par des fonds variant de 2 à 40 m. Les résultats indiquent que des tempêtes d'intensité moyenne pourraient produire des vagues et des courants forts, là où la profondeur d'eau est inférieure à 20 m. Selon les prévisions, les figures sédimentaires prédominantes sont des rides causées par des vagues et un fond plat dans les régions littorales de moins de 15 m de profondeur où la vitesse du courant soutenu est modérée. Cependant, un fond océanique prédomine plat lorsque la vitesse du courant soutenu est plus élevée. Les directions prévues de transport sédimentaire sont très sensibles à la direction des vagues. On a utilisé ces résultats pour choisir le site où ont été installés des instruments de surveillance du transport sédimentaire en février 2002.

INTRODUCTION

The Fraser River delta system is host to a number of major structures that have been constructed across the intertidal delta plain and onto the Fraser River delta slope (Fig. 1). These include the North Arm and Iona Island jetties on northern Sturgeon Bank, and the Steveston jetty forming the northern edge of the Main Arm distributary channel. Two major causeways cross southern Roberts Bank, providing access to the Deltaport container facility and Westshore Terminals coal port, and the B.C. Ferries Tsawwassen Terminal.

The combination of natural compaction, subsidence, channel confinement, dredging of the riverbed, and construction of significant structures across the delta plain has large potential for affecting the sediment balance of the delta. Barrie and Currie (2000) present a review of sediment distribution patterns on the tidal flats and foreslope of the delta and discuss several areas of concern where anthropogenic activities may have affected delta sedimentation patterns. The majority of southern Roberts Bank appears to be undergoing net erosion under present-day conditions. Conversely, the delta slope and prodelta to the north on Sturgeon Bank are currently accreting at rates between 1 and 10 cm a year, with the deposited materials consisting primarily of fine-grained sediments (Hart et al., 1998).

Given that the Fraser River delta is located in an area of high seismic activity, the presence of sensitive marine clays under the delta foreslope sediments (Christian et al., 1997), and the possibility of considerable damage to infrastructure on the delta during an earthquake event (Barrie and Currie, 2000), the Geological Survey of Canada is investigating the nature of erosive processes on the upper delta foreslope. This work is being carried out under the Georgia Basin Geohazards Initiative (GBGI), a major program aimed at understanding the geological processes and conditions that represent hazards to the Canadian population in the regions surrounding the Georgia Basin.

From a review of the literature, P.R. Hill (unpub. rept., 2001) developed a conceptual model for sediment transport in the intertidal, nearshore, and slope areas of the Fraser delta. Three main hypotheses were presented in the conceptual model:

1. Roberts Bank is the area of the delta most susceptible to rapid erosion.
2. The erosion of Roberts Bank is related to a zone of sediment transport divergence located between the outer tidal flats and the delta slope. In shallower water on the tidal flats, net sediment movement is in the onshore direction; in deeper water on the delta slope, net sediment movement is in the offshore or downslope direction.
3. The presence of tidal channels on the delta flats will lead to a high degree of alongshore variability in the sediment transport regime, as offshore flows during the ebb tide are concentrated in the channels.

A combined field measurement and numerical modelling program is planned to test these hypotheses (P.R. Hill, unpub. rept., 2001). As a preliminary part of this work, the SEDTRANS96 numerical modelling package was used to simulate sediment transport conditions on the foreslope of Roberts Bank. The objective was to estimate the potential sediment transport on the upper delta foreslope under a range of wave and current conditions and as a function of water depth to provide insight for the design of a detailed measurement program to be carried out in the winter of 2002.

PHYSICAL SETTING

Roberts Bank covers the intertidal delta between the Main Arm channel and Point Roberts headland (Fig. 1). The intertidal flats narrow from approximately 8 km at the northern end to zero at Point Roberts. South of Main Arm, the outer edge of the tidal flats present a southwest-facing linear shoreline at low tide, suggesting strong wave reworking. Several tidal channels intersect the low-tide shoreline and form small ebb-tide deltas. In the vicinity of the Deltaport and ferry terminal, the low-tide line defines a natural broad embayment that has been artificially exaggerated by dredging of a turning basin east of the Deltaport.

Offshore, the seabed slope steepens markedly to 5° or 6° below about 5 m water depth on the linear northern section, and below 10 m on the embayed southern section (water depths relative to chart datum). The delta slope begins to flatten again below 50 m on both northern and southern Roberts Bank. The mean grain size of seabed sediments is close to 3 ϕ, or 0.125 mm (fine sand), on both the intertidal flats and upper delta slope (Barrie and Currie, 2000). A field of large subaqueous dunes characterizes the foreslope seaward of the embayed low-tide shoreline (Kostaschuk et al., 1995).

CURRENTS

Tides in the southern Strait of Georgia are mixed, mainly semidiurnal, with two tidal exchanges per day. The combination of strong diurnal and semidiurnal tidal constituents creates inequalities in both the height and the timing of successive high and low waters, with the inequalities varying over fortnightly and longer time scales. In the southern Strait of Georgia, the regional characteristics of the tidal cycle are such that larger tidal exchanges often occur on a monthly rather than a fortnightly basis.

Water-level measurements at the Tsawwassen ferry terminal (Fig. 1) show a tidal range of 3.0 m on a mean tide and 4.7 m on a large tide. To the north at Sand Heads (Fig. 1), tidal ranges are 3.1 m and 4.8 m, respectively (Canadian Hydrographic Service, 2000). Tidal currents flow essentially parallel to the bottom contours along the delta slope, i.e. northwest-southeast along Roberts Bank. There is some suggestion that flood-tide currents (to the north or northwest) may be stronger and of longer duration than ebb-tide currents (Thomson, 1981; Kostaschuk et al., 1995). Current-meter data from the fall of 1992 (Kostaschuk et al., 1995) indicate

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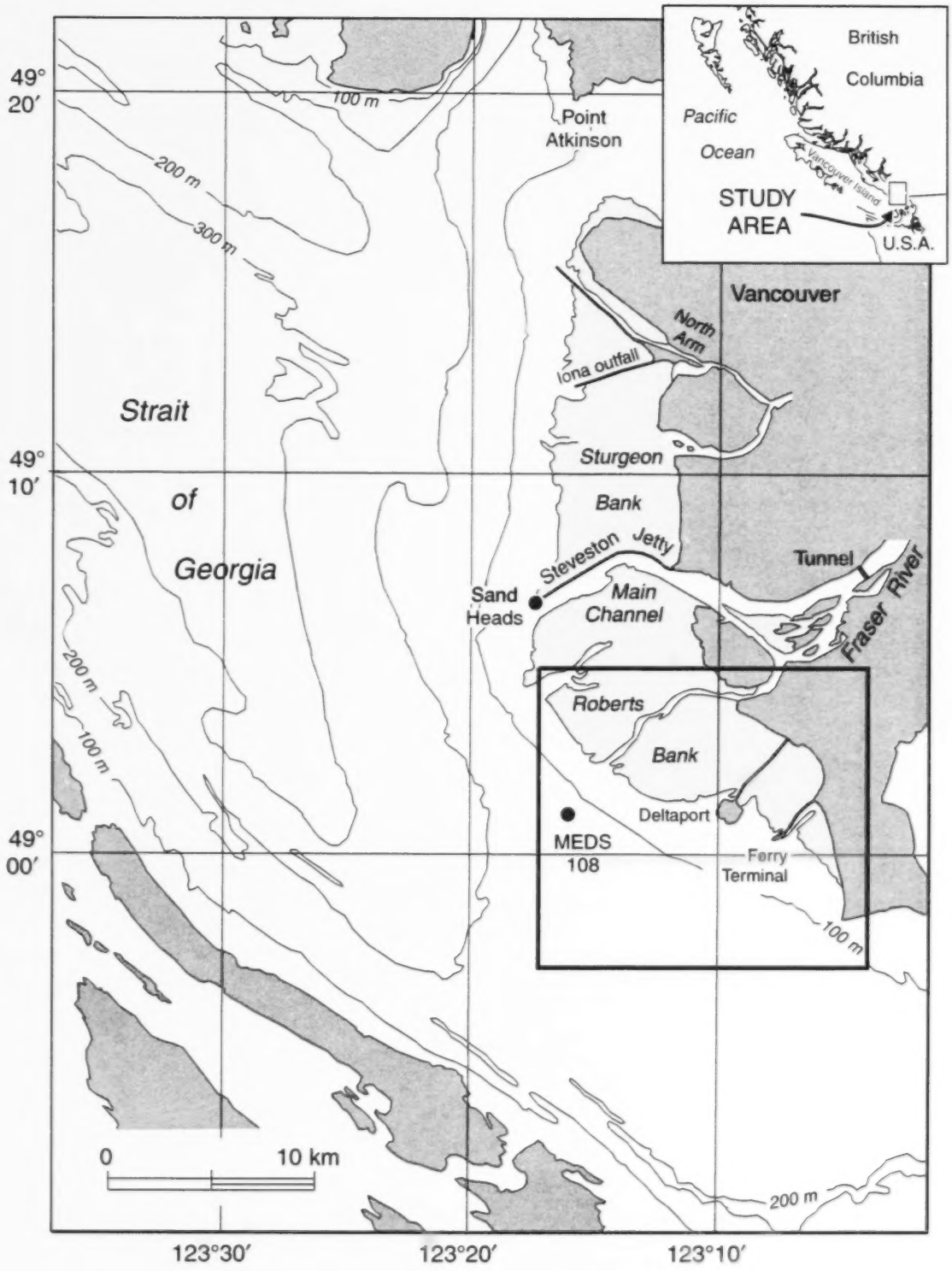

Figure 1. *Location map of the Fraser River delta. The general study area on Roberts Bank is indicated.*

that currents at 90 m water depth on the foreslope south of the Westshore Terminals are strongly bidirectional with shore-parallel currents several times stronger and less variable than the cross-shore current components. Also, currents are stronger and more persistent in the flood-tide direction, particularly during weaker tidal exchanges when flow reversal on the ebb tide does not always occur.

SURFACE WAVES

The oscillatory currents associated with surface waves often play a major role in seabed erosion and sediment transport, particularly in shallow waters on exposed coastlines. Although the Fraser River delta is not exposed to large storm waves, wave-induced oscillatory currents would still be large enough to play a significant role in sediment movement on the delta front.

Surface waves are driven by storm winds, both local and distant. As a result of the protection provided by Vancouver Island, the Fraser River delta is exposed primarily to waves generated by local winds over the Strait of Georgia. Regional winds are predominantly from the southeast during the winter months and from the northwest in summer. Over the Strait of Georgia, local wind patterns reflect the combined influence of regional winds, local topography, and winds driven by continental weather systems (e.g. outflow winds).

For the purposes of this project, a review of historic wind data from the Sand Heads Light Station was conducted for the period from 1967 through 1990. At Sand Heads, the most common wind directions are from the east, southeast, and northwest, together accounting for roughly 65% of the total observations. Southerly and westerly winds each occur roughly 10% of the time, with winds from the north, northeast, and southwest each accounting for less than 5% of the measurements. On an annual basis, the strongest winds blow most frequently from the northwest and the southeast, although directionally averaged wind speeds are fairly consistent from all sectors except weaker northerlies and northeasterlies.

Actual measurements of wave conditions in the southern Strait of Georgia are limited. Wave data summaries for two stations have been obtained from the Marine Environmental Data Service (MEDS) of the Department of Fisheries and Oceans. Approximately two years of wave measurements were made in the mid-1970s at station MEDS 108.

The analyses for the entire period of record indicate that wave conditions in the southern Strait of Georgia are generally calm, showing significant wave heights of less than 0.5 m for more than 79% of the readings. For these relatively calm conditions, peak periods ranged from 2 s to 10 s, but were usually between 2 s and 4 s. The maximum significant wave height measured over the period of record was 3.4 m, during June 1981. The corresponding peak period was approximately 7.5 s.

For the purposes of sediment transport analyses, storm-wave conditions can be considered to include two cases, the first, in which wave heights are relatively high with moderate periods, and the second, in which periods are long, but wave heights are not necessarily high. A review of the data indicates that for 3.7% of the record, significant wave heights are greater than 1.0 m. The average significant wave height for these higher waves is 1.3 m and the average peak period is 5.0 s. For 2.4% of the time, wave periods are longer than 6.0 s. The average significant wave height for these longer period waves is 0.3 m and the average peak period is 6.8 s.

In general, the low, long-period waves measured near Roberts Bank are likely to have been generated by lower speed winds blowing over longer fetches. From station MEDS 108 near Roberts Bank, available fetches are limited, with the longest fetch length to the northwest (80 km). Fetches to the southeast are roughly half as long (45 km), and fetches to the west (20 km) and south (16 km) are considerably shorter. Using the wind speeds at Sand Heads, both the northwest and southeast fetches are sufficient to generate wave fields with peak periods exceeding 6.0 s. However, the winds from the southeast are only strong enough to generate these long-period waves for roughly 0.8 days/year. Consequently, it seems reasonable to assume that the low, long-period waves arrive at the Fraser River delta primarily from the northwest.

Using similar arguments, one can show that the waves greater than 1.0 m in height could be generated by winds from the west, south, southeast, or northwest. Winds from the west and south are strong enough to generate these waves for roughly 1% of the time, or about 3.5 days/year. This would leave the remaining 2.7% of the observations, or 10 days/year, with waves generated by winds from either the northwest or the southeast. Thus, it would appear that once again, wave fields with significant heights greater than 1.0 m arrive offshore from Roberts Bank primarily from the southeast or the northwest, with some contribution from the south and the west.

These two storm-wave conditions represent events occurring, on average, for roughly 22 days/year. During the rest of the year, conditions are relatively calm. Analysis of the remaining wave data indicates an average significant wave height of approximately 0.3 m, with a mean peak period of 3.4 s. However, it is not clear whether periods of calm are included in these data points, a factor that may influence the mean values. These waves could be generated by winds from any direction, although the directional distribution is likely to be similar to that of the winds, with the northwest and southeast directions dominating.

FRASER RIVER DELTA SEDIMENT TRANSPORT MODELLING

Description of the SEDTRANS96 model

SEDTRANS96 is a one-dimensional numerical model that predicts sediment transport under steady currents or combined wave and current flows (Li and Amos, 1997). The model uses the combined-flow bottom boundary layer model of Grant and Madsen (1986) to predict velocity profiles and bed shear stress, the algorithms of Einstein-Brown (Brown, 1950)

Table 1. Parameters used in the SEDTRANS96 modelling runs presented in this study.

Parameter	Description	Values
Seabed:		
D	sediment grain size	0.00125 m
ρ_s	sediment density	2650 kg·m^{-3}
η	ripple height	0.02 m
λ	ripple wavelength	0.10 m
β	seabed slope	2–5 m: 0.6°
		5–10 m: 2.2°
		10–30 m: 6.3°
		30–40 m: 5.2°
Water Column:		
h	water depth	2–40 m, in 1 m increments
ρ	fluid density	1025 kg·m^{-3}
Currents:		
u_z	steady current speed	*see* Table 2
z_r	reference height above seabed	2.6 m
C_{dir}	direction of current	295° true
Waves:		
H_s	significant wave height	*see* Table 2
T_p	peak period	*see* Table 2
W_{dir}	wave direction	*see* Table 2
Sediment transport:		
F	option number for transport equation	2 (Brown, 1950)

Table 2. Wave and current parameters for the cases modelled in this study.

Case number	u_z (m·s^{-1})	H_s (m)	T_p (s)	W_{dir} (° true North)
1	0.25	1.3	5.0	SE (315)
2	0.25	1.3	5.0	W (90)
3	0.25	1.3	5.0	S (0)
4	0.45	1.3	5.0	SE (315)
5	0.25	0.34	3.4	SE (315)
6	0.45	0.34	3.4	SE (315)
7	0.25	0.3	6.8	SE (315)
8	0.25	no waves		
9	0.45	no waves		

and Yalin (1963) to predict bedload, and the methods of Engelund and Hansen (1967) and Bagnold (1963) to determine total load transport (sum of bedload and suspended load). An additional feature of the model is its prediction of bedform type on the basis of empirical predictors determined by Li and Amos (1998, 1999). A full description of the model can be found in Li and Amos (1997).

Model input

The model was applied to the southern Roberts Bank area for a variety of wave and current conditions, based on seabed, current, and wave information described above. The input data required for the SEDTRANS96 model are summarized in Table 1, along with the values of each parameter used. The various combinations of current and wave parameters used in the study are summarized in Table 2. The sediment properties listed in Table 1 represent typical values for southern Roberts Bank rather than values for a specific location. In the absence of any information on bedforms or bottom roughness, ripple height and spacing of 2 cm and 10 cm, respectively, were assumed for the start of each model run.

Current parameters were chosen to represent conditions during a relatively large tidal cycle and during a relatively small cycle, from a visual assessment of available current records (Kostaschuk et al., 1995). The indicated current speeds were selected to represent values exceeded for one or two hours during each cycle. Current directions were assumed to be essentially parallel to the bottom contours at all water depths. Currents on the flood tide were assumed to be similar to those on the ebb tide.

Wave conditions were chosen to represent both moderate and storm conditions. Given the uncertainty in wave direction, a number of propagation directions were considered. However, the focus of this assessment was on waves from the southeast.

As waves move from deep water into shallower depths, wave heights and wavelengths change in response to shoaling and refraction processes. As waves enter shallower waters, bottom friction acts to slow the wave propagation speed and, under certain conditions, can lead to significant increases in wave height. Wave refraction acts in a similar matter, causing bending of the wave crests such that alignment with the seabed contours increases as water depth decreases. Wave refraction can lead to either increased or decreased wave heights, depending on the incident wave angle and the bottom topography. Wave shoaling and refraction effects are both strongly dependent on the wave period.

For southern Roberts Bank, waves arrive primarily from the southeast, west, and south. Waves from the southeast and west arrive at a high angle of incidence to the shore, causing significant refraction and spreading of the available wave energy over an increasing surface area as the waves approach the shoreline. This effect starts to occur in water depths of 35 m, 19 m, and 8 m for wave periods of 6.8 s, 5.0 s, and 3.4 s, respectively.

For the purposes of this project, a simplified wave refraction and shoaling analysis was conducted for the various wave conditions outlined in Table 2. Monochromatic wave fields were assumed, and linear wave theory was used to assess the change in wave height and wavelength for waves of a given period approaching a beach with linear, parallel

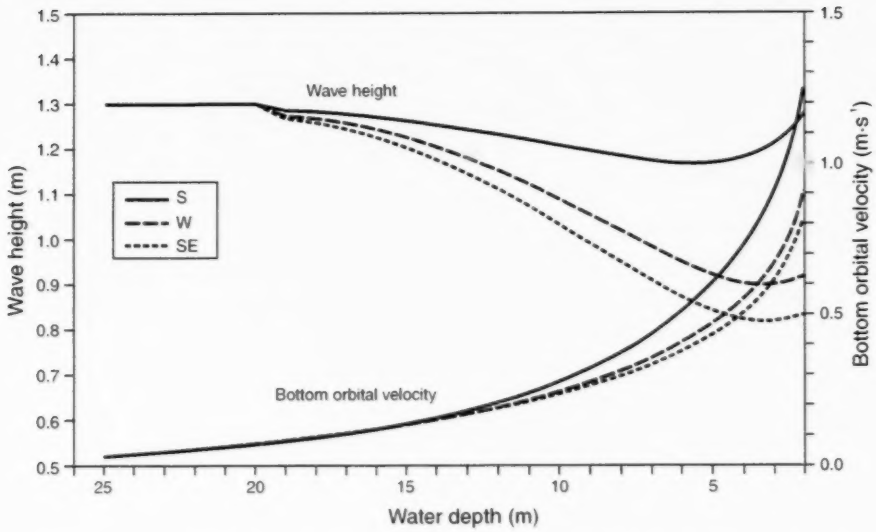

Figure 2. *The effects of deep-water wave direction on nearshore wave heights and bottom orbital velocities for waves with a 5.0 s period approaching southern Roberts Bank.*

bottom contours. The impacts of wave refraction and shoaling on wave heights and bottom orbital velocities for 5.0 s waves approaching southern Roberts Bank from the southeast, west, and south are shown in Figure 2. Significant attenuation of the wave height due to refraction can be seen for incident waves with oblique orientations with respect to the delta slope. The shoaling effect is observed in water depths of less than 4 m, where the wave heights increase slightly. As predicted from linear wave theory, bottom orbital velocities increase exponentially with decreasing water depth.

MODEL RESULTS

An example of typical model results where waves are present (case 1, Table 2) is shown in Figure 3, plotted as a function of water depth shoaling from 40 m to 2 m. As the water depth decreases and wave orbital velocities increase (Fig. 3a), the model predicts an evolution of bedform type (Fig. 3b). From depths of 40 m to 33 m, equilibrium current-dominated ripples would be stable, but in shallower water, these ripples begin to decay (entering the 'break-off region' of Grant and Madsen, 1982). This is manifested by a decrease in ripple height with constant ripple length. The bed eventually becomes a plane bed in water depths of less than 10 m. The sharp increase in ripple height and wavelength corresponding to the transition from equilibrium to break-off ripples is an artefact of the different empirical formulae used in the model for these parameters. For equilibrium ripples, the bedform steepness (height/length) is held constant for a given grain diameter and the ripple height is a function of the bedload shear velocity. In the break-off region, by contrast, the ripple length is held constant and the bedform steepness is a function of bedload shear velocity (Li and Amos, 1997). The sudden decrease in ripple length at the transition from break-off wave-dominated ripples to plane bed is also an artefact. As the ripple height decreases to zero, the ripple length no longer has meaning.

The sediment transport rates for both suspended load and bedload increase as water depth decreases (Fig. 3c). Once again, the rapid changes in transport rates at the equilibrium to break-off and ripple to plane bed transitions are artefacts of the empirical predictors used in the program. In deep water, the suspended load transport rate is predicted to be greater than two orders of magnitude higher than the bedload transport rate, but bedload transport increases more rapidly than suspended load transport as orbital motions increase in shallow water. Of significance is the change in net bedload transport direction. For this case of waves approaching from the southeast, the net transport changes progressively from a current-dominated alongshore direction (295°TN) to an oblique onshore direction (325°TN), suggesting a divergence of sediment transport beginning in approximately 20 m water depth (Fig. 3d).

Cases 1 to 3, for different wave directions with the same mean current speed (0.25 $cm \cdot s^{-1}$), show similar results in terms of bedload transport rates (Fig. 4a) and the water depths in which major bedform transitions take place (Table 3). There are significant differences, however, in the predicted bedload transport directions (Fig. 4b). For waves from the south, the computed direction of bedload transport turns obliquely onshore up to 10 m water depth, then reverts to a more alongshore direction in shallower water. Under westerly wave approach, the predicted transport direction turns progressively toward the offshore. The reason for this is not

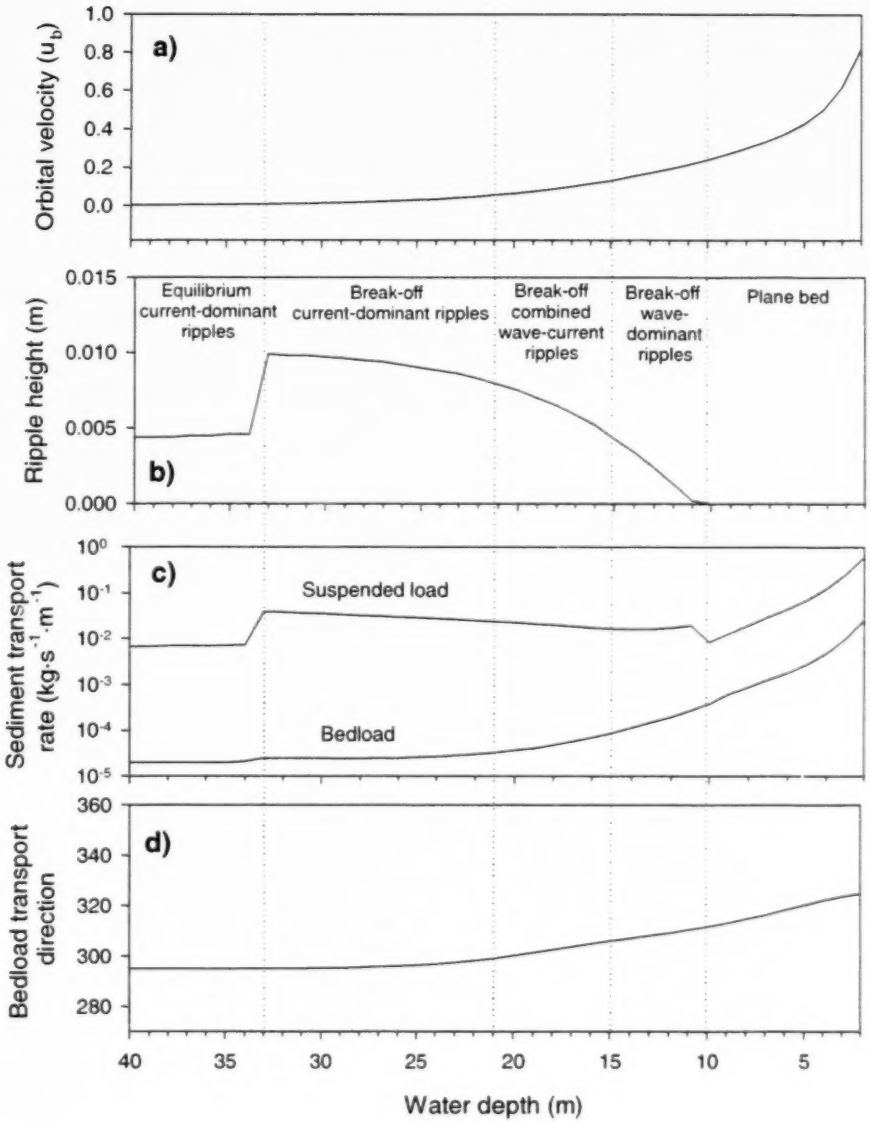

Figure 3.

*Model results for case 1 (u_z = 0.25 m·s^{-1}; H_s = 1.3 m; T_p = 5 s, W_{dir} = SE); **a**) orbital velocity; **b**) ripple height; **c**) sediment transport rate for bedload and suspended load; d) bedload transport direction. Data presented as a function of water depth.*

Table 3. Summary of the water depths (in metres) of major bedform transitions for the model runs shown in Table 2.

Case	Break-off current-dominated ripples	Combined wave and current ripples	Wave-dominated ripples	Plane bed
1	33	21	15	10
2	33	21	15	11
3	29	19	15	11
4	>40	16	Not predicted	13
5	13	7	3	Not predicted
6	>25	4	Not predicted	3
7	>40	14	3	Not predicted
8	Current ripples only			
9	Current ripples only			

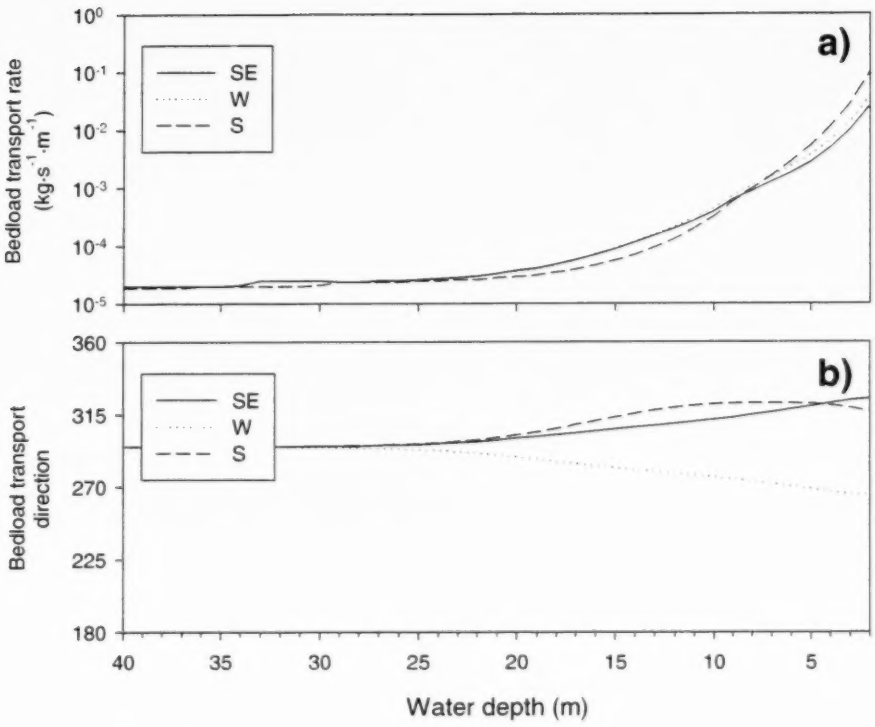

Figure 4.

Comparison of cases 1 to 3 (u_z = 0.25 m·s^{-1}; H_s = 1.3 m; T_p = 5 s, W_{dir} = SE, W, and S); a) bedload transport rate; b) bedload transport direction. Data presented as a function of water depth.

clearly understood at this time although it is critical for understanding sediment transport on the delta foreslope and, therefore, requires further study.

Cases 4 and 6 were run to determine the effect of a higher mean current (0.45 m·s^{-1}). In both these cases, the zone of break-off current-dominated ripples expands into both deeper and shallower water and the plane bed field expands into deeper water (Table 3). As a result, the model predicts that wave-dominated ripples would not be stable at any water depth.

In the two cases with very weak wave-induced bottom currents (cases 5 and 6), the model was found to be numerically unstable in deeper water. Under these conditions, the model run terminated at the instability before transport rates could be calculated. The same bedform stability fields were noted in shallower water, but in all cases the transitions occurred at shallower depths (Table 3).

DISCUSSION

The modelling exercise provided important information with respect to the siting of future measurement programs. A sediment transport instrument package was deployed in March 2002 with the objective of providing baseline information on combined wave and current conditions for future sediment transport modelling efforts. Given the uncertainty of wind conditions over the relatively short deployment period (1 month), the deployment site was required to have active combined-flow and potentially variable bedform configurations under moderate storm conditions. On the basis of the modelling presented in this paper, the site was chosen in a water depth of 10 m.

The results of the modelling study also highlight several important factors that need to be taken into account in future field-based and modelling studies. First, to determine zones of sediment transport divergence and convergence that would indicate areas of potential erosion and deposition respectively, it is necessary to have a precise knowledge of wave direction. The modelling was carried out for a single point with only simple refraction and did not take into account the temporal changes in wave parameters that would typically occur during a storm. Future model development should attempt to address this issue.

Second, a good understanding of the current field is required. The model runs used two steady current velocities, 0.25 and 0.45 m·s^{-1}, based on data from considerably deeper water (90 m; Kostaschuk et al., 1995). Initial results from acoustic doppler current profiler (ADCP) measurements during the summer of 2001 suggest that the current regime off Roberts Bank varies along slope and that maximum current speeds may locally exceed 1 m·s^{-1} (S. Meulé, pers. comm., 2001). Future modelling will thus also have to take into account the spatial and temporal variability of the strong tidal currents in the region.

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